Radiative smoothing for smoothed clouds

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Introduction

Marshak et al. (1995) formulated an elegant model that predicts the impact on measured radiances made by horizontal fluxes of photons (Marshak and Davis 2005). They explain, quite reasonably, that horizontal fluxes act to smooth out details of cloud structure at scales smaller than about 300 m, and thus are responsible for breaks in scaling that are observed in radiance wavenumber spectra and structure functions. It is argued here that the magnitude of observed radiance scale breaks cannot be explained by radiative smoothing coupled with pure scaling clouds. It seems necessary that relevant cloud structures exhibit a corresponding scale break at radiative smoothing scales thereby augmenting the effects of radiative smoothing.

Marshak/Davis analyses

- Marshak and Davis et al. claim:
  - if horizontal transport was minimal (e.g., as in the IPA model or in extremely dense media), radiances would scale like the medium (Fig. 1)
  - LWP (or τ) for StCu clouds scales like $k^{-5/3}$ below scales at which radiance scale breaks are observed
  - deviation of radiance spectra (and structure functions) from $k^{-5/3}$ at these scales is due to radiative smoothing

The essence of radiative smoothing

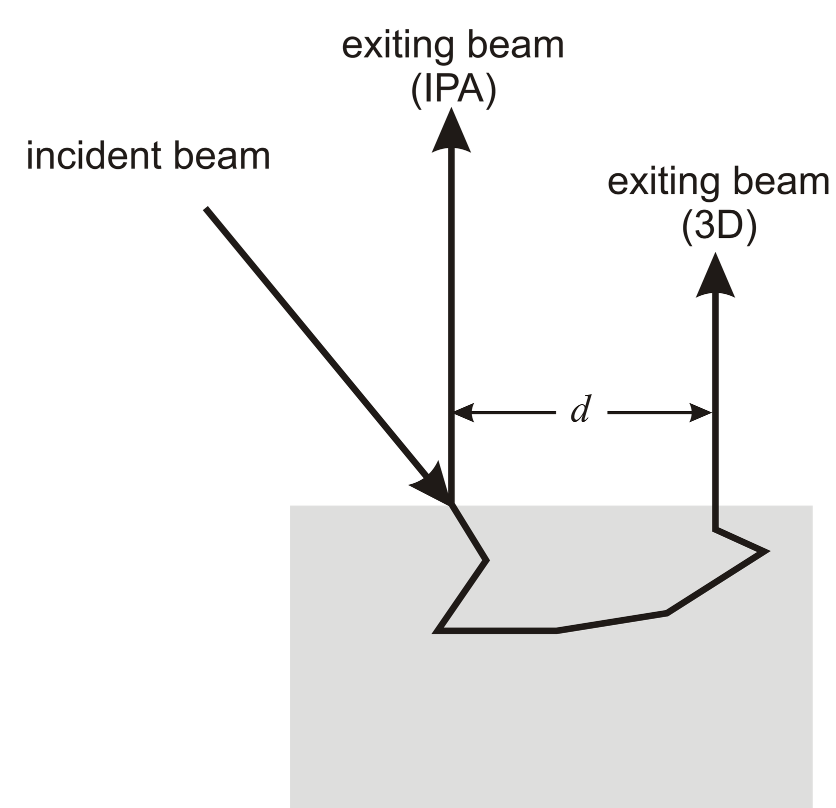


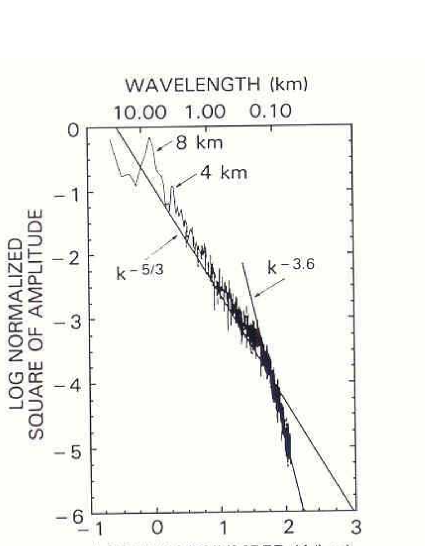
Fig. 1. In the IPA model, photon entry and exit points are at the same location. Since photons are free to travel in all directions, lateral distances between entry and exit points are generally $d > 0$. Multiple scattering acts effectively like a low-pass filter thereby suppressing cloud information.

- predicted scales at which radiative smoothing breaks occur (Marshak et al. 1995):

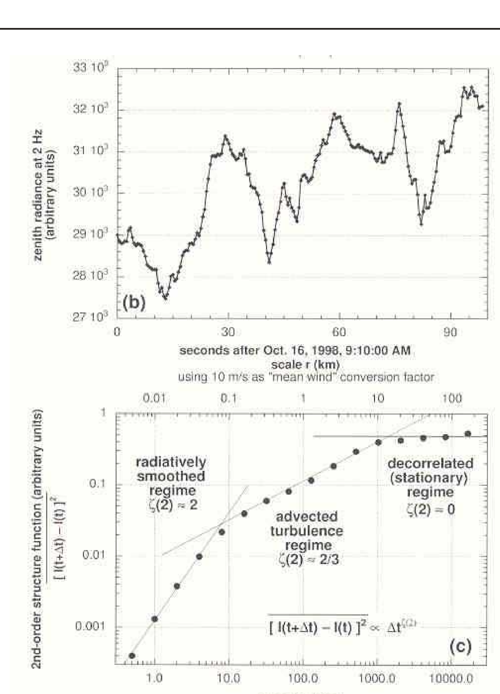
$$\eta_R \propto \frac{\langle h \rangle}{\sqrt{(1-g)\,\langle \tau \rangle}} \quad \text{reflected radiance}$$

$$\eta_T \propto \langle h \rangle \quad \text{transmitted radiance}$$

- two examples showing typical scale breaks:



satellite
(Cahalan + Snider 1989)



surface
(Marshak and Davis 2005)

Fig. 2. Radiative smoothing as demonstrated by satellite imagery and a zenith directed radiometer. Note that slopes of the wavenumber spectrum β often change from 5/3 to between 3 and 4, while slopes of the structure function ζ (= β - 1) often change from 2/3 to between 2 and 3.

Standard vertical cascade clouds

- bounded cascade (Cahalan et al. 1994)
  - each experiment:
    - 10 steps (1024 cells in one direction); Δx = 25 m
    - thickness = 250 m; <τ> = 10
    - Henyey-Greenstien (g = 0.85; conservative)
    - 10 member ensembles

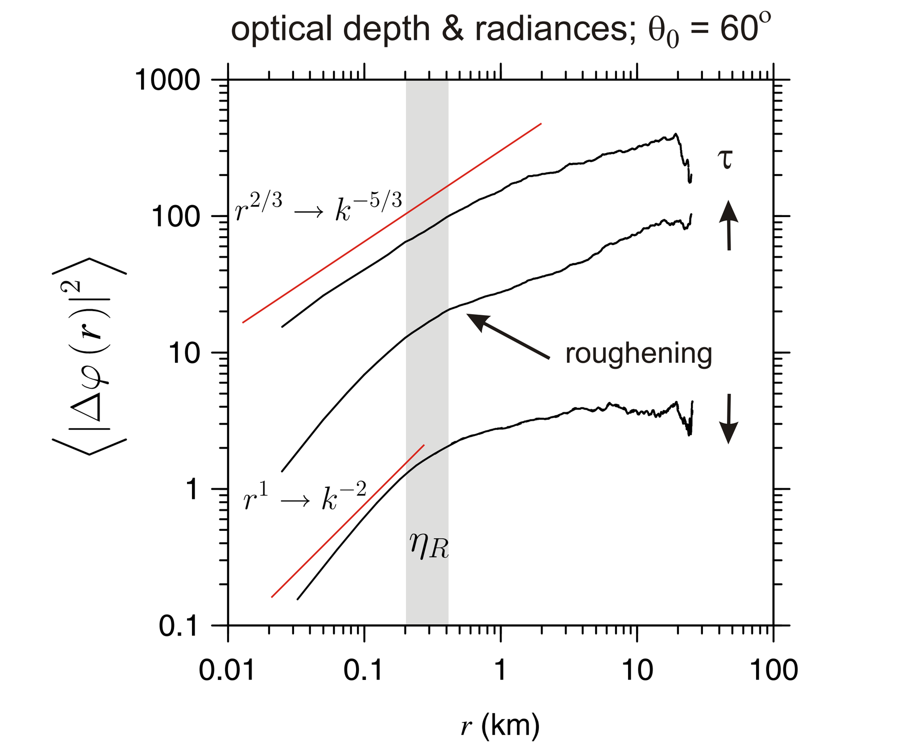


Fig. 3. Ensemble average second-order structure functions for optical depth and nadir ↑ and zenith ↓ radiances (arbitrary placement). Radiative smoothing is obvious at scales that agree with theory (200 m < η_R < 400 m), but it is less pronounced than for measurements; expecting small-scale regimes closer to r^2 (k^{-3}) for radiances.

Simple modifications to idealized clouds

Simple ways to realize a smoothing (i.e., scale break) in clouds at scales similar to the radiative smoothing length, but still maintaining $k^{-5/3}$ for horizontal fluctuations in LWC at small scales (in accord with aircraft data):

1. r_e is an increasing function of LWC → corresponding extinction fluctuations are suppressed → no impact on scales larger than typical cell size (i.e., placement of cloud cells in 2D plane) or on LWC spectra

2*. adiabatic clouds that are dense near tops (large LWC) → closer to IPA, and less smoothing

3. isotropic variability of LWC → vertical integral through cloud yields $E(LWP) \sim k^{-8/3}$ at scales less than typical cell size (see Barker and Davies 1992)

4. any vertical correlation < 1 for LWC

5. possibly strong vertical correlation for LWC, but advect rising and falling cloud parcels → slanted clouds with scale break in LWP near typical cell size

Slanted cascade clouds

- same clouds as above:
  - 10 layers; each 25 m think
  - each layer shifted laterally by (n - 1) * 25 m where n is layer number

three types of idealized *clouds*

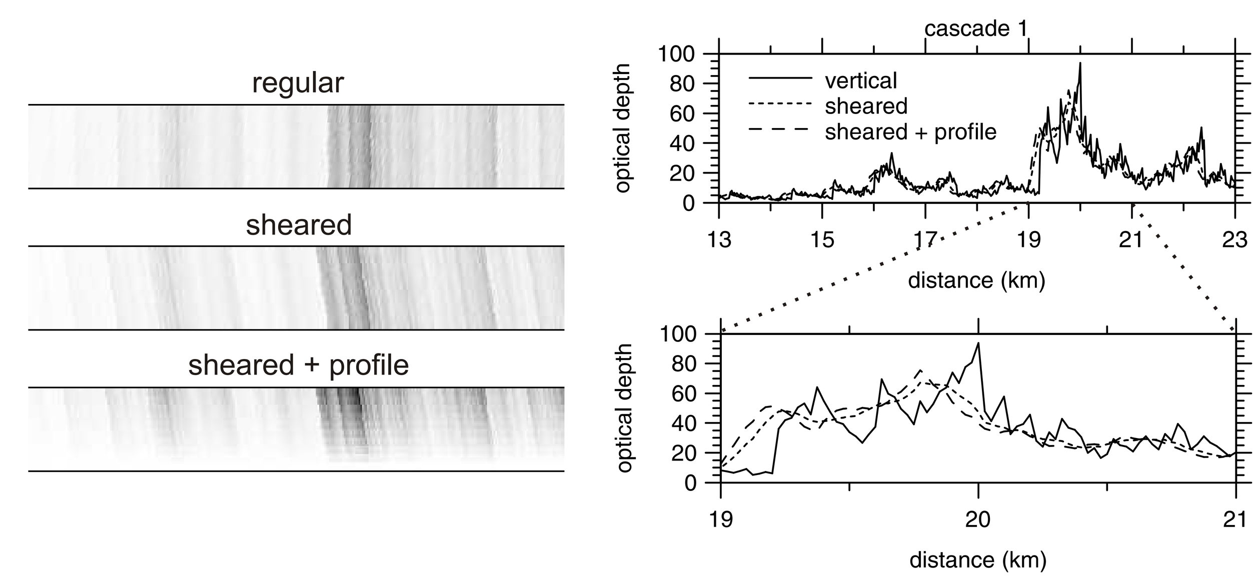


Fig. 4. 10 km segments of cascade clouds all generated with the same sequence of random numbers. The *sheared + profile* field has LWC increasing linearly from 0 at the base before lateral shifting. All fields exhibit $k^{-5/3}$ wavenumber spectra for LWC measured along horizontal transects. Plots on the right show that for this 10 km segment, transects of total optical depth differ for all fields, though they all have domain averages of <τ> = 10.

Impacts on spectra due to cloud structure

- Monte Carlo photon transport:
  - 32,768,000 photons/field; 32,000/column
  - black underlying surface
  - no scattering by air or aerosols (λ > 0.6 μm)

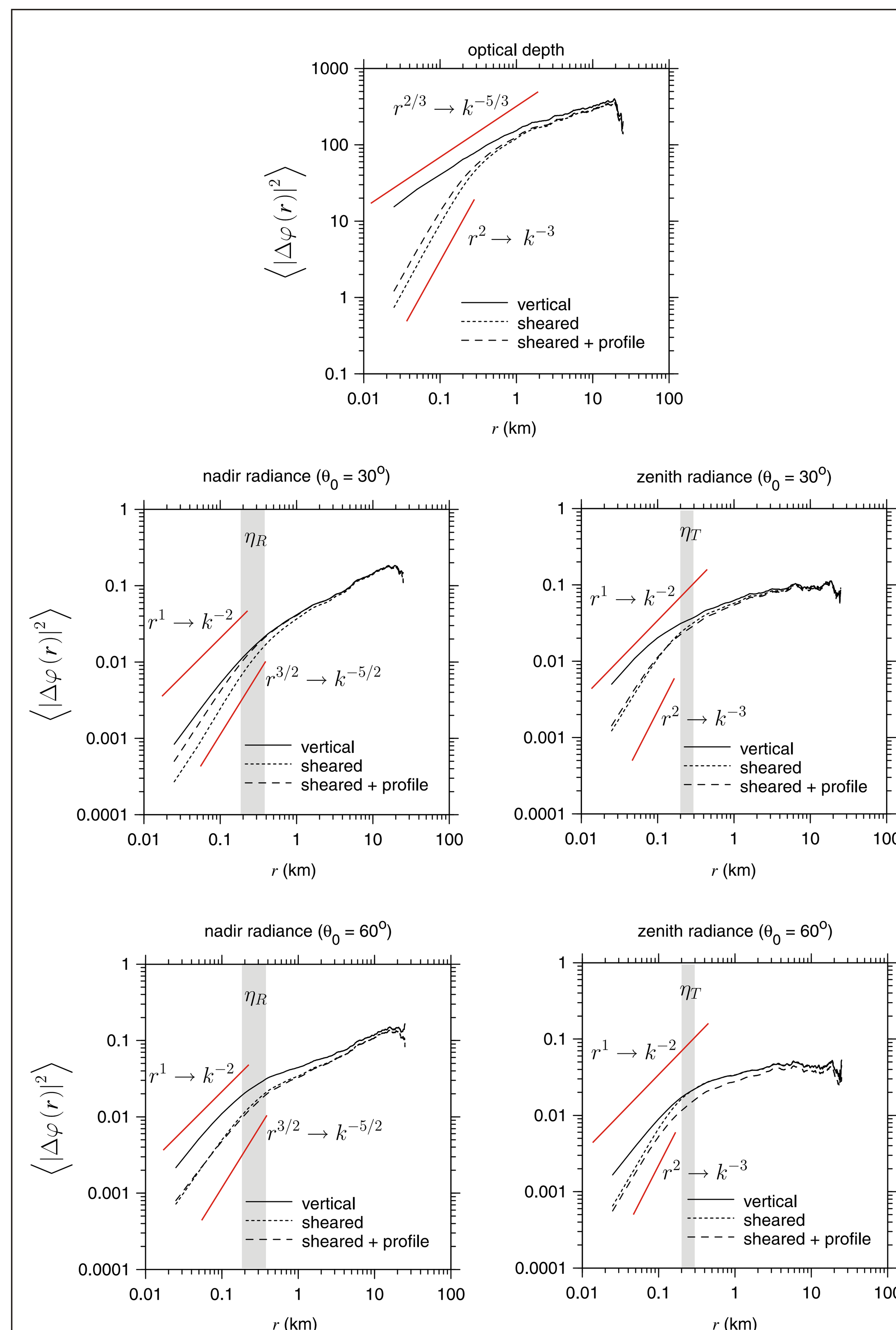


Fig. 5. Top plot shows ensemble average <ϕ^2> for τ for the three fields shown in Fig. 4. Despite their obvious differences, <ϕ^2> for the sheared fields resemble each other closely and differ from the conventional field. Other plots show <ϕ^2> for nadir and zenith radiances at two solar zenith angles θ_0:

1. unlikely to distinguish *sheared* from *sheared + profile*
   - difficult to comment on cloud structure by appealing to radiative smoothing only?
2. sheared fields exhibit steeper spectra in smoothing regime;
   - especially for zenith radiances... close to measurements

Conclusions and questions

- radically different cloud structure can give rise to similar spectra and structure functions (see Fig. 5)
- slopes of radiance spectra in the smoothing regime for clouds with spectra for τ that scale like $k^{-5/3}$ are not steep enough
- to produce slopes similar to those for observations, some 'smoothing' has to be done to clouds
- placement of *cells* in a plane follow $k^{-5/3}$... once 'inside' cells (below roughening scales), clouds have to be smoothed (yet maintain $k^{-5/3}$ for LWC transects)
- these results do not go against radiative smoothing... they suggest that there's more to the slope of the wavenumber spectra in the smoothing regime than just radiative smoothing
- these results should not impact the performance of a NIPA-style model... they just somewhat complicate setting of the Green's function parameters

References

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